# Automated Coordinated Mission Planning Across Constellations

Mark Abramson, Brian Collins, Stephan Kolitz, Michael Ricard, Pete Scheidler, Charles Strauss
The Charles Stark Draper Laboratory, Inc.
Cambridge, MA 02139

*Abstract*– **Draper has been developing a simulation testbed, the Earth Phenomena Observing System (EPOS), which includes an automated mission manager. The automated mission manager will reduce requirements on the human operators of satellites, improve system resource utilization, and provide the capability to dynamically respond to temporal terrestrial phenomena. Examples of triggering events are localized transient phenomena that have a significant impact on human life such as volcanic eruptions, weather (hurricanes, tornadoes, etc.), biomass burning (e.g., forest fires). The current effort is focusing on the Morning and Afternoon ("A Train") Constellations. The goal of these Constellations is to provide correlative measurements that will yield unprecedented cloud, climate, aerosol, and chemistry science.**

**We are using MODIS Cloud Mask data from the MODIS instrument on Terra (in the Morning Constellation) as input into EPOS's mission manager. The EPOS mission manager uses this data to plan the pointing of the TES instrument on Aura (to be launched in 2004 as part of the A Train). In particular, TES pointing plans include high-value locations of interest that are not covered with clouds.**

**We analyzed the timeliness of the Terra and Aqua MODIS data for use in this operational concept and found that for the 1400+ volcanoes found at the Smithsonian Institution Global Volcanism Program[1] the great majority of the data is timely for tasking TES and results in improved science data gathering. We present an overview of current enhancements being made to EPOS that will provide additional capabilities in optimized tasking of sensors for science data collection.**

## I. Operational Concept

A significant trend in the design of systems of Earth observing satellites is the notion of multiple spacecraft working collaboratively. One class of collaborative satellites is a confederation[2], a group of heterogeneous, non-interacting satellites observing similar phenomena in near real-time. Our effort is focused on enhancing the capability to improve the science data gathering of a confederation of satellites by changing the non-interacting nature of confederations to interacting, through the explicit use of data gathered from one or more satellites to influence the data gathered from others. Our initial focus is on real-time cueing, which refers to taking measurements made by one or more sensors on one satellite and using them in real-time to cue the tasking of another satellite's sensors. Data from a cueing satellite will provide the situation awareness and assessment for use in real-time dynamic tasking of one or more sensors on later[3] satellites.

The initial example of real-time dynamic tasking we are addressing is to use MODIS data from Terra and Aqua, processed into the form of MODIS Cloud Mask data, to point TES, an instrument that will be on Aura when it is launched, currently planned for early 2004. TES, which will be used to observe volcanoes and biomass burning, cannot see through clouds. MODIS data is directly broadcast[4] on X-band and is potentially available in near real-time. In addition, we will combine the MODIS Cloud Mask data with the cloud mask data generated from geosynchronous weather satellites, e.g., GEOS-8, for further improvement in the forecast of cloud cover at the time TES can observe the area on the ground.

## II. Concept Analysis

The MODIS data from Aqua would be ideal for providing a forecast of cloud cover for TES tasking, because Aqua will be only a few minutes ahead of Aura in observing regions on Earth. However, there is no processing capability on Aqua nor will there be direct communication between Aqua and Aura. In the operational concept described in Section I, delay between reception of the Aqua MODIS broadcast data and any possible tasking of TES results from data processing and communication time needed to generate a MODIS Cloud Mask from the broadcast data, run the EPOS Mission Manager[5] and send tasking commands to TES. We assume for the purpose of illustration in the following that the minimum time between broadcast of the MODIS data and pointing of TES at high-value locations of interest that are not covered with clouds is 60 minutes.

The following describes our initial analysis of the operational concept.

1. http://www.volcano.si.edu/gvp/volcano /vbd_geog.htm
2. Raymond, C. A., J. O. Bristow, and M. R. Schoeberl, Needs for an Intelligent Distributed Spacecraft Infrastructure, Earth Science Vision Session, IGARSS 2002, Toronto, Canada
3. Later is measured by the times satellites can observe a given location on Earth.
4. http://modis.gsfc.nasa.gov/data/directbrod.html
5. EPOS is described in "Real-Time Optimized Earth Observation Autonomous Planning," M. Abramson, et al, in Proceedings of the 2002 Earth Science Technology Conference, Pasadena, CA, June 2002.

## A. *TIMELINESS ANALYSIS*

Figure 1 shows in the left-most picture in yellow the swath[6] of the MODIS sensor on Terra[7] at time 16:27:10 UTC on November 5, 2002. Superimposed in cyan is the expected groundtrack of Aura[8] (if it were in its expected orbit).

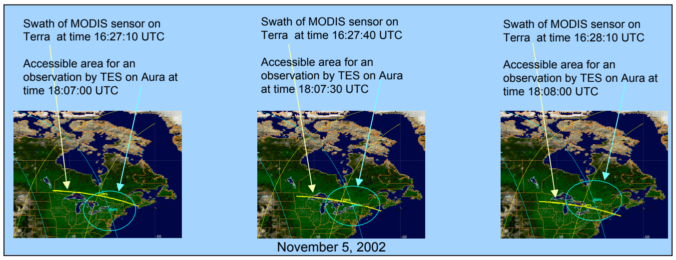


**Figure 1: MODIS and TES Coverage**

Aura is shown in the position it would occupy at approximately 18:07 UTC (one revolution after the MODIS data has been obtained). The TES instrument on Aura will be pointable[9] to access any target within 45° of the local vertical; the region of feasible pointing directions for TES is bounded by the oval shown. The center picture in Figure 1 shows Terra at time 16:27:40 UTC (30 seconds later) and Aura at time 18:07:30. The right-most picture in Figure 1 shows Terra at time 16:28:10 UTC and Aura at time 18:08:00. Figure 1 clearly indicate that MODIS data, from the instrument on Terra, can be used to forecast where cloud cover will be approximately 100 minutes later, and hence can be used to increase the value of the science gathered by TES.

We next examined the case of a single volcano, Kilauea in Hawaii. There were 20 possible observations of Kilauea by TES over the course of a full 16 day groundtrack cycle. As illustrated in the histogram in Figure 2, Terra/MODIS data is timely for TES tasking to view Kilauea in Hawaii, i.e., there are more than 60 minutes to account for communication and processing delay in each observation, but the times are short enough to improve the performance of TES by improving the chances of avoiding cloud cover over locations of interest on Earth.

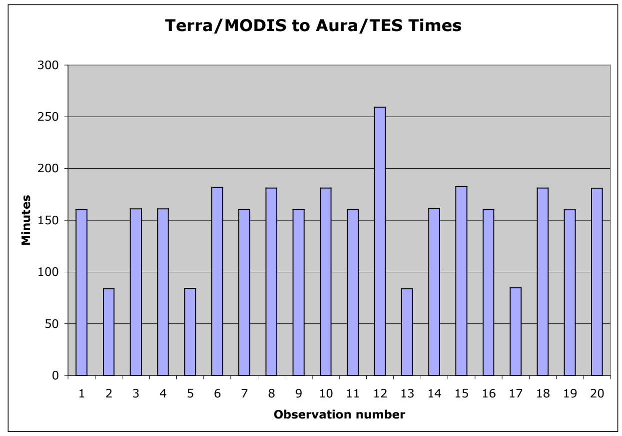


**Figure 2: 20 Possible Observations of Kilauea in a 16 Day Cycle**

Our final step in the initial analysis of the operational concept is illustrated in Figure 3 in which the minimum times greater than 60 minutes between MODIS observations and TES observations are plotted for all 1400+ volcanoes listed at the Smithsonian Institution Global Volcanism Program's web site. The results show that the great majority of the Terra/MODIS data and a substantial amount of the Aqua/MODIS data are timely for tasking TES to view the 1400+ volcanoes unobstructed by cloud cover.

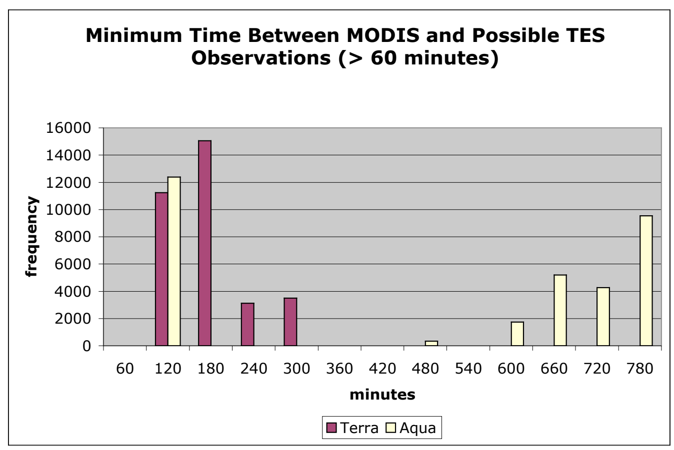


**Figure 3: Frequency Distribution of Minimum Times Between MODIS and Possible TES Observations**

## B. *PERFORMANCE ANALYSIS*

We used EPOS to analyze the performance of the operational concept for the following examples. Figure 4 illustrates the tasking decisions EPOS made for TES for the volcanoes shown as green squares on the map without taking into account any information about cloud cover. The decisions in the red oval are for locations under the cloud cover, shown by a notional cloud on the map in Figure 4.

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6 http://terra.nasa.gov/About/MODIS/modis_swath.html

7 Orbit elements for Terra are from http://www.celestrak.com/NORAD/elements

8 Orbit elements for Aura were derived from Aqua's, from ftp://modis-dbc.gsfc.nasa.gov/ephemeris/tle/aqua.tle

9 http://tes.jpl.nasa.gov/INSTRU/instru_m.html

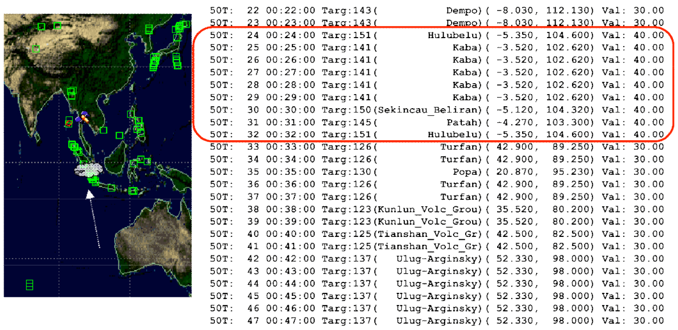


**Figure 4: Tasking Without Using Cloud Mask Data**

Figure 5 illustrates the results when target observations were planned using cloud mask data as input for EPOS. The result is that the non-obscured targets in grey are selected in the plan, replacing the previous entries in the red box. Utilizing the cloud mask data in planning increases the realized science value of TES observations.

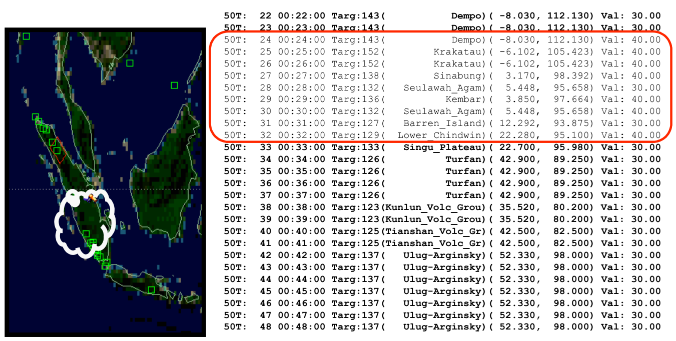


**Figure 5: Tasking Using Cloud Mask Data**

## III. EPOS DEVELOPMENT

This section describes some of the ongoing work in our continued EPOS development. Figure 6 illustrates, at a high level, the functions in the current version of EPOS.

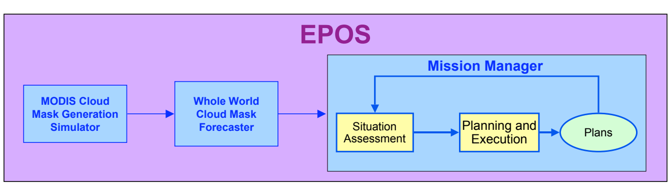


**Figure 6: EPOS Functions**

The MODIS Cloud Mask Generation Simulator uses historical MODIS Cloud Mask data ordered from the EOS Data Gateway[10] to produce a simulated feed of real-time MODIS Cloud Mask data to the Whole World Cloud Mask Forecaster. This forecaster produces a forecast of the cloud cover for any location of interest (e.g., volcanoes, forest fires) on Earth to the Mission Manager. The forecaster is a simple model at this point, using the most recent observation as the forecast to produce the "Whole World Cloud Mask." The EPOS Mission Manager was enhanced to utilize this forecast as input to Situation Assessment, which decides when to replan, and what metrics to optimize, in Planning and Execution. We are continuing to use our ADEPT[11] architecture for the Mission Manager.

### Whole-World Cloud Mask Data

One of the issues in developing the Whole World Cloud Mask Forecaster is the storage of a Whole World Cloud Mask, whether it consist of actual data or of forecasts of the cloud mask.

MODIS Cloud Masks are generated in "granules," which are roughly 20 degrees by 20 degrees regions on Earth, using five minutes of MODIS data. The Whole World Cloud Mask Forecaster requires the storage of a whole earth cloud mask with a 1 kilometer by 1 kilometer resolution, taken from the granule-sized updates coming from the Cloud Mask Generation Simulator every five minutes of simulated time. Keeping the cloud mask data in granule form would require at least 50 GB of data storage to cover the Earth, for two reasons:

1) The granules overlap, so many granules would have to be kept in order to maintain full Earth coverage.
2) Data in a granule is not aligned on a grid; thus, although each cloud mask datum for a 1 kilometer by 1 kilometer region is only one byte long, four bytes each for the latitude and longitude of that datum must be maintained. Each granule requires 24 MB for storage.

The following data storage scheme addresses these problems. Starting with longitude -180°, lay out 1 kilometer by 1 kilometer cells along the equator (both north and south). There will be 40,075 cells in each line (since the earth is 40,075.16 kilometer in equatorial circumference) before longitude +180° is reached. This process is repeated, going both north and south. For the first several rows, 40,075 cells will be needed in each row. Soon, though, fewer will be needed to reach from –180° to +180° longitude, decreasing as the cosine of the latitude decreases. There are 20,004 rows from pole to pole. The total number of cells is 510,394,994 which is about one-half a GB.

Our cloud mask data, one byte per cell, will be maintained on this grid. The following information will be maintained for each row:

- Latitude (in degrees) of side of row closest to equator.

[10] http://redhook.gsfc.nasa.gov/~imswww/pub /imswelcome/

[11] Ricard, M. and S. Kolitz, "The ADEPT Framework for Intelligent Autonomy," in VKI Lecture Series on Intelligent Systems for Aeronautics, von Karman Institute, Belgium, May 13-17, 2002.

- Width of a cell in degrees of longitude (measured halfway between top and bottom of a cell)
- Offset into the big (one-half GB) array.
- Number of cells in row.

With this information, locating a particular cell given its longitude and latitude will be a simple computation, in effect making the determination of the cloud mask at any given longitude and latitude an indexed look-at rather than a laborious look-up procedure.

As granule data is added to the existing cloud mask data (either for initial establishment of the world cloud cover or as an update for use in the Whole World Cloud Mask Forecaster) the data in granule form will be discarded but the boundaries and date/time stamp for the granule will be saved. In this way the origin of the data in any cell can be easily determined, by searching back through a date/time-sorted granule boundary list.

### Higher Fidelity Satellite and Sensor Models

The models shown in Figures 7 through 10 represent an object-oriented design of higher fidelity models than previously implemented in EPOS. These are required to more accurately model the Morning and Afternoon Constellations and other Earth observing assets. Additionally, new uses of EPOS require more sophisticated features such as multiple sensors per satellite and a model of user data products tied to sensor collection bands.

Each of these new models is characterized by the dark blue label placed vertically across one or more model subcomponents. For example the Communication Model consists of the Communication Network and Communication Station model subcomponents. Each subcomponent has a light blue band naming the subcomponent. The subcomponents are described in detail below. Below the name are two yellow rows of boxes defining the parameters of the model. Below this is a gray-shaded row providing data as an example of the model.

### Satellite

There are two types of satellites that EPOS models: 1) Earth sensing satellites and 2) satellites that are part of a communication network. Both types of satellites have several parameters in common, which are specified in the Basic Satellite component. The Ephemeris details are broken out as a separate component that is part of every Basic Satellite. We model the notion of multiple communication networks that the satellite may utilize. The Sensing Satellite can have multiple sensors associated with it. The Basic Satellite description also lists several parameters that are planned additions to the model.

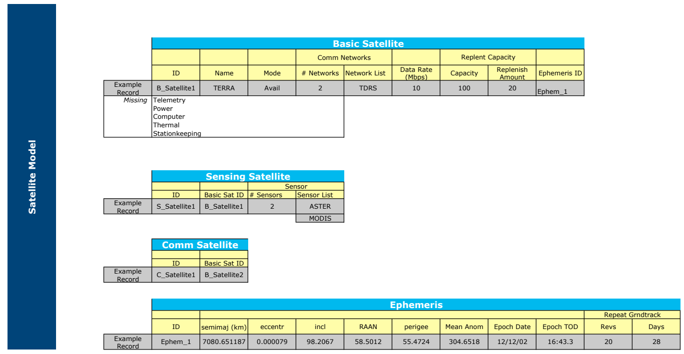


**Figure 7: Satellite Model**

### Sensor

The sensor model includes scanning field of view (FOV) sensors in addition to conical FOV sensors. Each of these FOV models is described by a rich set of parameters – only an initial subset is specified in the figure. The basic Sensor subcomponent has the addition of data bands, with different data measurements being captured in different bands. A modes parameter describes key operational configuration of the sensor.

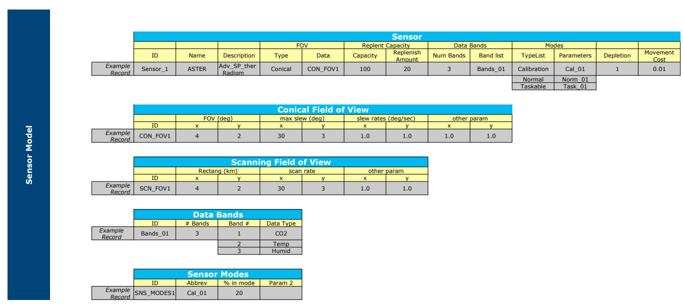


**Figure 8: Sensor Model**

### Communication

The communication model consists of communication stations and networks that the stations belong to. Satellites also belong to one or more communication networks. Communication stations can be for any combination of upload (commands), and download (data, telemetry). A communication station, for example, might only be used to download science data.

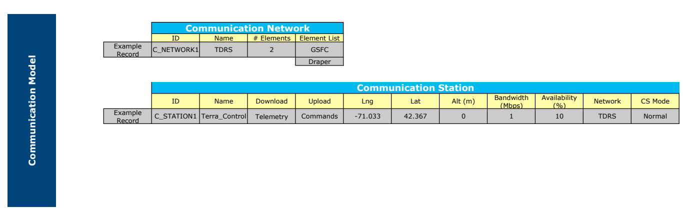


**Figure 9: Communication Model**

### Data products

The data products model connects the user community to the lower level science data coming from the satellites. This is a key enabler for some of the use cases that will drive the EPOS design.

**Data Products Model**

| | Data Products | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Measurements | | | | |
| | ID | Abbrev | Description | # Msrmnts | Data list | Required? | Processing Time | Processing Expense |
| *Example Record* | DataProd_1 | AtmHumid | Atmospheric Humidity | 3 | CO2 | n | 3 | 25 |
| | | | | | Temperature | n | | |
| | | | | | Pressure | y | | |

**Figure 10: Data Products Model**

### Planning

The Planning function in the Mission Manager will be modified to include a higher fidelity constrained optimization formulation, both in the objective function and the constraints, based on the new satellite and sensor models. The set of decisions being optimized, which previously included when and from where to gather observation data, will be extended to include additional decisions, e.g., moding (which mode to be in at what time) and communication (what data will be transmitted by which means at what time).


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